

MANUFACTURING METHODS AND VACUUM OR
HERMETICALLY PACKAGED MICROMACHINED
OR MEMS DEVICES FORMED THEREBY HAVING
SUBSTANTIALLY VERTICAL FEEDTHROUGHS

5 CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. provisional application
Serial No. 60/419,446, filed October 18, 2002.

BACKGROUND OF THE INVENTION

1. Field of the Invention

10 This invention relates to manufacturing methods and vacuum or
hermetically-packaged-micromachined or MEMS devices formed thereby having
substantially vertical feedthroughs.

2. Background Art

Low-cost vacuum packaging of MEMS has become one of the most
15 important challenges in the MEMS industry for a number of emerging applications
including resonant sensors and RF MEMS. Many different packaging technologies
have been developed over the years, including hermetic and vacuum packaging of
MEMS. There are many requirements for a MEMS package. These include small
size, vacuum/hermetic capability, integrated sealed feedthroughs, wafer level
20 processing, compatibility with most MEMS processes, reliability, stability in the
face of exposure to harsh environmental conditions such as
temperature/humidity/vibration, and of course, above all, low cost. Unfortunately
for the MEMS manufacturer, most of these requirements have to be satisfied at the
same time. A package that cannot be fabricated at low cost, or is too large, or
25 cannot provide feedthroughs, will not find many applications. This is where the
challenge lies to further advance the field of MEMS sensors and microsystems.

Many technologies have been developed for MEMS over the past few decades. One of these technologies is the so-called dissolved-wafer process (DWP) as described in U.S. Patent Nos. 4,815,472 and 5,377,524. The process forms heavily boron-doped silicon microstructures on a glass substrate. Electrical connections are made to the silicon microstructures using metal lines deposited on the glass substrate. This process has been used to produce many different types of sensors, actuators, and microsystems, and has been specifically used to manufacture one of the highest performance gyroscopes for inertial applications developed originally by Draper Lab. An important requirement for the successful operation of the gyroscope is that it should be operated in vacuum for many years. Therefore, a stable vacuum packaging technology is needed for this device.

S. Cho developed a vacuum package for this device based on bonding a glass capsule to the device glass substrate using an intermediate layer of high resistivity polysilicon as described in U.S. Patent No. 5,837,562. Feedthroughs were formed from gold lines. During the bonding process, these gold lines interdiffused with the high resistivity polysilicon through a eutectic process to form sealed feedthroughs. The eutectic was able to reflow and therefore cover over the steps created by the gold lines. Although some data for the vacuum capability of this package was presented, no long term data has been presented. The electrical connections for this packaging approach were brought out as gold lines on the device glass substrate. Bonding pads were brought out to the edge of the chip and could be used for wire bonding. The fact that bonding pads were used on the same side as the device meant that additional die area was used. In addition, it was not easy to flip chip attach this die to a circuit board.

The following U.S. patents relate to semiconductor variable capacitance pressure transducers and methods of making same wherein one of the named inventors is also a co-inventor of at least one of the inventions described and claimed herein: 4,261,086; 4,277,814; and 4,386,453.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a low-cost manufacturing method and vacuum or hermetically packaged micromachined or MEMS device formed thereby having at least one substantially vertical feedthrough
5 wherein a minimum amount of die area is used.

In carrying out the above object and other objects of the present invention, a method for manufacturing a vacuum or hermetically packaged micromachined or MEMS device having at least one substantially vertical feedthrough is provided. The method includes: providing a micromachined or
10 MEMS device fabricated on a first side of a substrate and located within a vacuum or hermetic cavity; forming at least one hole completely through the substrate between first and second sides of the substrate after the step of providing; and forming a path of electrically conductive material connecting the micromachined or
MEMS device and the second side of the substrate through the at least one hole to
15 form the at least one substantially vertical feedthrough.

The substrate may be a glass substrate.

The vacuum or hermetic cavity may at least partially be defined by a capsule connected to the substrate at a bonding area.

The micromachined or MEMS device may include at least one
20 microstructure.

The at least one microstructure may include a doped-semiconductor or metal microstructure.

The method of manufacturing may further include forming a plurality of electrical leads on the first side of the substrate in communication with the
25 micromachined or MEMS device.

The step of providing may include the step of bonding a capsule to the substrate to form the vacuum or hermetic cavity and wherein the step of forming may include the step of partially forming the at least one hole from the first side before the step of bonding.

- 5 The step of forming the at least one hole may include the step of etching the substrate at the second side of the substrate.

The step of forming the path may include the step of depositing a layer of electrically conductive material on the second side of the substrate and in the at least one hole.

- 10 The method may further include placing a solder ball or paste in the at least one hole on the layer of electrically conductive material.

The method may further include bonding a wire to the layer of electrically conductive material.

- 15 The layer may be deposited in the bonding area on the second side and wherein the method may further include placing a solder ball or paste on the layer of electrically conductive material at the bonding area.

The method may further include removing material from the second side of the substrate to thin the substrate before the step of forming the at least one hole.

- 20 The capsule may be anodically bonded or eutectically or solder bonded at the bonding area.

- Further, in carrying out the above object and other objects of the present invention, a method for manufacturing a vacuum or hermetically packaged micromachined or MEMS device is provided. The method includes: providing a
25 wafer and a substrate having first and second sides; partially forming at least one

hole in the first side of the substrate; bonding the wafer to the substrate to obtain a device substrate after the step of partially forming; fabricating a micromachined or MEMS device from the wafer after the step of bonding; positioning a capsule having a concave surface on the device substrate over the micromachined or MEMS device;

5 bonding the capsule to the device substrate to form a vacuum or hermetic cavity enclosing the micromachined or MEMS device and to form a bonding area which provides a hermetic seal around the vacuum or hermetic cavity; thinning the substrate down; finish forming at least one hole completely through the substrate between the first and second sides after the step of thinning; and forming a path of

10 electrically conductive material connecting the micromachined or MEMS device and the second side of the substrate through the at least one hole.

The substrate may be a glass substrate.

The capsule may be a silicon or glass capsule.

The micromachined or MEMS device may include at least one

15 microstructure.

The at least one microstructure may include a doped-semiconductor or metal microstructure.

The method may include the step of forming a plurality of electrical leads on the first side of the substrate in communication with the micromachined or

20 MEMS device.

The step of partially forming the at least one hole may include the step of removing material from the substrate to form at least one recess in the first side of the substrate before the step of bonding the wafer to the substrate.

The step of thinning may include the step of etching the substrate at

25 the second side of the substrate after the step of bonding the capsule to the device substrate.

The step of forming the path may include the step of depositing a layer of electrically conductive material on the second side of the substrate and in the at least one hole.

5 The method may further include placing a solder ball or paste that could be heated to form a solder ball in the at least one hole on the layer of electrically conductive material.

The method may further include bonding a wire to the layer of electrically conductive material.

10 The method may further include depositing the layer at the bonding area on the second side and wherein the method may still further include placing a solder ball or paste on the layer of electrically conductive material at the bonding area.

15 The step of thinning may include removing material from the second side of the substrate to thin the substrate after the step of bonding the capsule to the device substrate and before the step of finish forming the at least one hole is completed.

The step of bonding the capsule to the device substrate may include the step of anodically bonding the capsule to the substrate.

20 The step of bonding the capsule to the device substrate may include the step of eutectically or solder bonding the capsule to a peripheral portion of the semiconductor device to minimize outgasing into the vacuum or hermetic cavity.

25 Further in carrying out the above object and other objects of the present invention, a vacuum or hermetic packaged micromachined or MEMS device which is manufactured in accordance with at least some of the above steps is provided.

instead use wire bonding 18 to metal lines 20 formed on the back side of the device glass substrate 12. Below, the process is described in more detail.

Figure 1 illustrates not only one embodiment of the general structure of the package, but also shows a number of different options, as discussed below.

5 Before this discussion, a detailed process sequence is presented. As stated above, MEMS devices 22 are preferably fabricated using the standard DWP process. A silicon wafer containing the MEMS is first bonded to the device glass substrate 12 and then dissolved away to free up the MEMS structures or devices 22. The glass substrate 12 is a substrate with standard thickness (usually in the range of 500-

10 700 μm), or if possible it may be no more than 100 μm in thickness. However, an ultra-thin substrate may not be able to withstand the normal handling typically encountered in wafer processing. In any case, a standard thickness glass substrate will most likely be used. One can optionally form a shallow ($\sim 50\mu\text{m}$) recess 24 in the areas where the vertical feedthroughs are to be formed. The reason for forming

15 these shallow recesses 24 is to simplify the formation of the rest of the feedthrough hole, generally indicated at 25, from the opposite side of glass substrate 12, as will become clear later. The recesses 24 can be formed by wet etching, sandblasting, or perhaps by DRIE etching.

After the recesses 24 are formed in the glass substrate 12 and the

20 silicon wafer is bonded to the glass wafer or substrate 12 and dissolved away, the device substrate processing is complete, and the package capsule or wafer 10 can now be bonded to the device substrate 12. The bonding of the silicon cap or wafer 10 can be done using two ways: 1) the silicon cap 10 can be directly bonded to the glass substrate 12 using anodic bonding, as shown at 27 in Figure 1; or 2) a silicon

25 cap 10' can be bonded to a p++ rim, formed around the die when MEMS 22' are crated, using Si-Au eutectic bonding or using solder bonding, as shown in Figure 2 at 27'. The latter approach may be better since one may be able to avoid the anodic bonding process, and thus minimize outgasing into the vacuum cavity.

At this point, one has a sandwich of two wafers, one is the silicon

30 wafer 10 or 10' on top which forms the package (and is 500 μm thick if one assumes

4" wafers), and the other is the glass wafer 12 or 12', respectively, which supports the MEMS 22 or 22', respectively, and is about 700 μ m thick (assuming one does not use a thin glass wafer).

5 There is a need to create the feedthrough holes 25 or 25' in the glass substrate 12 or 12', respectively, to form the vertical feedthroughs. To do this, it is much easier if one had a thin glass substrate. However, as previously mentioned, the thick glass wafer can be thinned down from the backside. This can be done in a number of different ways: 1) chemical-mechanical polishing; or 2) simple wet etching. The latter technique works here because the entire front side of the wafer 10 12 or 12' is protected by the silicon cap 10 or 10', respectively, and therefore it is possible to leave the wafer combination in the glass etchant (typically HF acid) for a very long time until the glass substrate 12 or 12' is thinned to a thickness of about 100 μ m. This is potentially the most straightforward and lowest-cost approach to glass thinning.

15 Once the glass wafer 12 or 12' is thinned, one can etch the rest of the feedthrough holes 25 or 25' through it using a number of different techniques: 1) by using photolithography and wet etching in HF/HNO₃ and/or by dry etching such as RIE; 2) by using sandblasting; 3) by using laser etching or by using any other method of removing the material. This region of the feedthrough hole 25 is 20 indicated at 29 in Figure 1.

 Once the feedthrough hole 25 or 25' are completed, one now deposits a layer of gold to form the interconnect lines 20 or 20' on the back side of the wafer 12 or 12', respectively. This can be done using a simple shadow masking process since the feature sizes are large and since the glass substrate 12 or 12' has the deep 25 holes 25 or 25', respectively, formed in it already. The thin layer of gold is then electroplated up to a thickness of about 10 μ m to ensure that good step coverage is achieved and to provide additional coverage of the areas where the p++ silicon is bonded to the glass substrate 12 or 12' around the feedthrough holes 25 or 25', respectively. This electroplated gold layer 20 may be used as the base for forming 30 solder balls 14 and 16, as shown in Figure 1. A thin layer of Cr/Au may have to

be deposited to allow electroplating by providing electrical connections at the perimeter of the wafer.

5 The solder balls 14 and 16 are then formed on the back side of the glass substrate or die 12. The solder ball 14 is formed inside one hole 25 and the solder ball 16 is formed on the surface of the glass substrate 12 on the perimeter where a bonding ring or area 27 is located. Forming the solder ball 16 on the perimeter outside of the hole 25 may have the added advantages of: 1) being formed in a region where there is sufficient mechanical support provided by the silicon cap wafer 10; and 2) not being in the hole 25 and thus avoiding long-term stability
10 problems due to the thermal mismatch.

It is also possible to not use solder balls at all and simply use the wire bonding 18. In this latter case, the die is placed on a board on its backside, with the silicon cap 10 touching the substrate. This has the advantage of mechanically isolating the device from mechanical stresses induced by the board.

15 Figure 2 also shows a Pirani gauge, generally indicated at 30, which includes a heater 32 formed on a membrane 34. Contact metal 36, in turn, is formed on the heater 32.

The wafer is now ready to be diced using a standard saw to separate the individual dice. This can be done easily since the wafer is mechanically strong
20 (i.e., the silicon wafer 10 provides sufficient mechanical strength). This completes the process.

This vacuum packaging technology is superior to other approaches in many important ways. First, the MEMS parts 22 or 22' are protected during the entire process after they are released, so they cannot be damaged easily. Second,
25 the feedthrough holes 25 and 25' are substantially vertical, so precious die area is not consumed as it is with respect to lateral feedthrough approaches. Third, solder balls 14 and 16 can be easily formed for surface mount applications. Fourth, the package has sufficient mechanical integrity to allow it to withstand handling. Fifth,

all process steps are wafer level and involve only standard processing steps. Sixth, the packaging approach provides several alternatives at different steps, thus maximizing the chances of the package to work. And, finally, this process does not alter the fabrication process of the MEMS devices 22 and 22' and is done only after
5 the MEMS 22 and 22' are fabricated.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes
10 may be made without departing from the spirit and scope of the invention.